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Synergistic Effects of Rice Husk Ash and Pumice Powder as Supplementary Cementitious Materials in Blended Cement Concrete

Frank Ndanusa Williams ^{1*}, Daniel Nnaemeka Nwaigwe ², Amiara Chidiebere Afamefuna ³, Ijezie Stephen Chibuike ³

¹ Department of Building, University of Jos.

² Department of Building, Nigerian Building and Road Research Institute

³ Nigerian Building and Road Research Institute

*Correspondence should be addressed to Frank Ndanusa Williams, Department of Building, University of Jos. Email: williamsf@unijos.edu.ng

ABSTRACT

The growing demand for sustainable construction materials has intensified the search for supplementary cementitious materials (SCMs) capable of reducing Portland cement consumption. This study investigates the combined (synergistic) effects of rice husk ash (RHA) and pumice powder (PP) as partial cement replacements on the mechanical performance of concrete. Concrete mixtures incorporating varying proportions of RHA and PP were evaluated in terms of density, compressive strength, and flexural strength at curing ages of 7, 14, and 28 days. Statistical analyses, including regression modelling, correlation analysis, and analysis of variance (ANOVA), were conducted to assess performance relationships. Results indicate that density increased with curing age due to continued hydration, while compressive and flexural strengths decreased with increasing SCM content due to dilution effects. However, moderate replacement levels showed acceptable performance. A regression model developed for 28-day compressive strength exhibited strong predictive capability ($R^2 = 0.89$). The novelty of this study lies in the dual incorporation of agricultural and natural pozzolans, supported by statistical modelling to quantify interaction effects, providing new insights into sustainable concrete design.

Keywords: Rice husk ash, pumice powder, supplementary cementitious materials, blended cement concrete, compressive strength, sustainable construction

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1. INTRODUCTION

The global construction industry is experiencing rapid growth, which has significantly increased the demand for conventional construction materials such as Portland cement and fired clay bricks. However, the

production of these materials is associated with high energy consumption and substantial greenhouse gas emissions, particularly carbon dioxide (CO₂). Cement manufacturing alone contributes approximately 7–8% of global CO₂ emissions,

creating significant environmental concerns and motivating researchers to explore sustainable alternatives in construction materials development [1], [2]. In response to these challenges, considerable research has focused on the development of environmentally friendly construction materials that can reduce cement consumption while maintaining adequate structural performance. Among such approaches is the incorporation of supplementary cementitious materials (SCMs) derived from industrial and agricultural wastes into cement-based systems. SCMs not only improve concrete durability and long-term performance but also contribute to waste management and resource efficiency [3], [4]. One agricultural by-product that has received significant attention in recent years is rice husk ash (RHA). RHA is produced from the controlled combustion of rice husks generated during rice milling processes. Due to its high amorphous silica content, typically exceeding 70%, RHA exhibits strong pozzolanic characteristics and can react with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H) compounds [5], [6]. These secondary hydration reactions enhance the microstructure of cementitious materials and improve durability properties such as abrasion resistance, compressive strength, and resistance to chemical attack [7], [8]. The use of RHA as a partial replacement for cement has also been shown to reduce environmental impacts associated with cement production while simultaneously addressing agricultural waste disposal challenges. Large quantities of rice husk are produced annually in rice-producing countries, and improper disposal of this agricultural residue can lead to environmental pollution. The conversion of rice husk into ash for use in concrete production, therefore, provides a sustainable solution that promotes circular economy principles within the construction sector [9], [10]. In addition to agricultural wastes, naturally occurring pozzolanic materials such as pumice powder (PP) have been investigated as potential cement replacement materials. Pumice is a volcanic material rich in silica

and alumina that exhibits pozzolanic reactivity when finely ground. Its low density and porous structure make it suitable for producing lightweight and sustainable concrete mixtures [4], [8]. The combination of RHA and pumice powder has the potential to enhance the sustainability of concrete production by reducing cement consumption while improving microstructural properties.

Several studies have reported that incorporating pozzolanic materials into concrete mixtures can influence key properties such as workability, compressive strength, density, and water absorption. While early-age strength may decrease due to reduced clinker content, long-term strength development is often enhanced by the pozzolanic reactions occurring within the cementitious matrix [5], [6]. Furthermore, the refinement of pore structure associated with pozzolanic reactions can improve durability characteristics such as permeability and resistance to chemical attack [7], [11]. Despite extensive research on individual supplementary cementitious materials such as rice husk ash (RHA) and pumice powder (PP), limited studies have systematically investigated their combined (synergistic) effects on the mechanical performance of blended cement concrete, particularly using locally sourced materials in developing regions. Existing studies largely focus on single-material replacement or durability aspects, with insufficient attention to multi-variable interactions, statistical modelling, and performance optimisation [3], [8].

Therefore, this study addresses this gap by evaluating the combined influence of RHA and PP on density, compressive strength, and flexural strength, supported by regression modelling, correlation analysis, and ANOVA. The novelty of this work lies in: (i) the dual incorporation of agricultural and natural pozzolans, (ii) the development of a predictive statistical model for strength performance, and (iii) the provision of quantitative insights into material interaction effects, which are currently underreported in literature.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study consisted of Ordinary Portland Cement (OPC), fine and coarse aggregates, rice husk ash (RHA), pumice powder

(PP), and potable water. Ordinary Portland Cement conforming to BS EN 197-1 [12] and ASTM C150 [13] standards were used as the primary binder.

Natural river sand obtained from the Naraguta River near the University of Jos was used as fine aggregate, while crushed gravel served as the coarse aggregate. The aggregates were cleaned, air-dried, and graded in accordance with BS 882 [14] specifications for concrete production. Proper aggregate grading plays an important role in improving the workability, strength, and durability of concrete mixtures [14], [15].

Rice husk ash (RHA) was obtained from a rice milling plant in Idah, Kogi State, Nigeria. The rice husk was burnt at 500°C under controlled conditions, and the resulting ash was ground and sieved through a 150 µm sieve to obtain fine particles suitable for use as a supplementary cementitious material, as shown in Figure 1. RHA contains a high proportion of amorphous silica, which enables it to exhibit strong pozzolanic activity when incorporated in

cementitious systems [16]. The Physical and chemical composition of RHA is presented in Tables 1 and 2, respectively.

The Pumice powder (PP) was obtained from Gombe State, Nigeria. These pumice powders were collected as aggregates and then ground as shown in Figure 1, and were also used as a natural pozzolan due to their silica and alumina content, which contribute to secondary hydration reactions and improved concrete microstructure [4]. The chemical composition of the combined components of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ for PP is $77.83 > 70$, thereby classified as Class N pozzolans according to the guidelines stated in ASTM C 618 [17]. The Physical and chemical composition of PP is presented in Tables 1 and 2, respectively. Clean potable water conforming to BS EN 1008 [18] requirements was used to mix and cure the concrete specimens.

Table 1. Computation of Quantities of Constituents

Materials	Specific Gravity	Bulk Density
Cement	3.15	1440 Kg/m ³
Pumice powder	2.5	1550 Kg/m ³
Rice Husk Ash	2.5	1515kg/ m ³
Sand	3.1	1590Kg/m ³
Gravel	2.6	1520Kg/m ³

Table 2. Chemical Properties of Rice Husk Ash (RHA) and Pumice Powder (PP)

Constituent	composition of RHA (%)	composition of PP (%)
SiO_2	73.60	44.00
CaO	1.01	9.87
Al_2O_3	1.06	15.00
Fe_2O_3	0.78	17.83
MgO	1.31	0.81
K_2O	21.23	3.11
SO_3	0.14	0.31
LOI	18.20	0.01



Figure 1. Materials: a) Rice Husk, b) Rice Husk Ash, c) Pumice Aggregate, d) Pumice powder

2.2 Mix Proportion

Concrete mixtures were prepared using cement, fine aggregate, and coarse aggregate with a water–cement ratio of 0.5. Partial replacement of cement was carried out using rice husk ash and pumice powder at different proportions. The quantities of the constituent materials used in the concrete mixtures

were calculated based on the absolute volume method, and the corresponding mix proportions are presented in [Table 3](#). The use of SCMs in blended cement concrete reduces clinker content while maintaining acceptable strength and durability properties [19], [20].

Table 3. Mix design of the concrete used

PP (%)	RHA (%)	OPC (%)	Cement (kg/m ³)	RHA (kg/m ³)	PP (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)
0	0	100	350	0	0	700	1400	175
0	5	95	332.5	17.5	0	700	1400	175
0	10	90	315	35	0	700	1400	175
5	0	95	332.5	0	17.5	700	1400	175
10	0	90	315	0	35	700	1400	175

5	5	90	315	17.5	17.5	700	1400	175
5	10	85	297.5	35	17.5	700	1400	175
10	5	85	297.5	17.5	35	700	1400	175
10	10	80	280	35	35	700	1400	175

2.3 Preparation of Concrete Specimens

Concrete specimens were prepared using 100 mm × 100 mm × 100 mm steel cube moulds for compressive strength testing, and prismatic beam moulds were 100 mm × 100 mm × 500 mm for flexural strength testing (Figures 2a and 2b). Before casting, the moulds were cleaned and coated with a thin layer of oil to prevent adhesion between the concrete and the mould surfaces.

The fresh concrete was mixed thoroughly and placed into the moulds in three layers, with each layer

compacted using a 16 mm diameter steel tamping rod with 25 strokes per layer. The specimens were then vibrated using an electric vibrating table to remove entrapped air and achieve uniform compaction. After casting, the concrete surfaces were levelled using a steel trowel and covered to prevent moisture loss. The specimens were left in the moulds for 24 hours before demoulding.

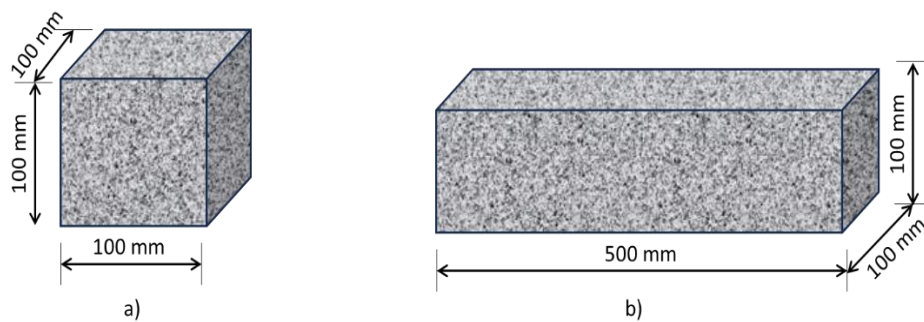


Figure 2. Specimen dimensions for a) the specimen's length, width, and height for compressive strength loading, and b) the specimen's length, width, and height for flexure strength loading.

2.4 Curing of Specimens

After demolding, the concrete specimens were cured by immersion in a water tank maintained at ambient laboratory temperature. The specimens were cured for 7, 14, and 28 days to allow proper hydration of the cementitious materials. Curing plays a critical

role in the development of the strength and durability of concrete because it facilitates hydration reactions that lead to the formation of cementitious compounds such as C-S-H gel [16].

2.5 Experimental Tests

2.5.1 Density Test

The density of the concrete specimens was determined by measuring the mass and volume of the cured concrete

cubes. Density was calculated using the expression:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \quad (1)$$

where:

Mass = weight of specimen (kg)

Volume = specimen volume (m³)

Density is an important parameter influencing the mechanical and durability properties of concrete.

2.5.2 Compressive Strength Test

Compressive strength tests were conducted in accordance with BS EN 12390-3 [21]. The concrete cubes were tested using a compression testing machine at curing ages of 7, 14, and 28 days. The load was applied gradually until failure occurred, and

the maximum load carried by the specimen was recorded.

The compressive strength of each specimen was calculated using:

$$f_c = \frac{P}{A} \quad (2)$$

where:

f_c = compressive strength of concrete (N/mm²)

P = maximum load applied at failure (N)

A = cross-sectional area of the specimen (mm²)

Compressive strength is widely used as the primary indicator of concrete performance and structural capacity [15].

2.5.3 Flexural Strength Test

Flexural strength tests were carried out to determine the resistance of the concrete specimens to bending stresses. The test was performed using the beam specimens in accordance with BS EN 12390-5 [22]. The beam specimens were placed on supporting

rollers and loaded gradually at the midpoint until failure occurred.

The flexural strength was calculated using the following expression:

$$f_r = \frac{PL}{bd^2} \quad (3)$$

where:

f_r = flexural strength (modulus of rupture) (N/mm²)

P = maximum applied load at failure (N)

L = span length between supports (mm)

b = width of the beam specimen (mm)

d = depth of the beam specimen (mm)

Flexural strength provides an indication of the tensile behaviour of concrete and its ability to resist bending

stresses in structural elements such as beams and slabs.

2.6 Statistical Analysis

Statistical analyses were conducted to evaluate the influence of rice husk ash (RHA) and pumice powder (PP) on the performance of blended cement concrete.

The analyses included regression analysis, correlation analysis, and analysis of variance (ANOVA). These statistical tools were used to

examine the relationships among the measured parameters and to assess the reliability of the experimental data.

2.6.1 Regression Analysis

Regression analysis was performed to determine the relationship between compressive strength and the percentage replacement of cement with rice husk ash

and pumice powder. The regression model adopted for the analysis is expressed as:

$$f_c = a + bR + cP \quad (4)$$

where:

f_c = compressive strength of concrete (MPa)

R = percentage replacement of cement with rice husk ash (%)

P = percentage replacement of cement with pumice powder (%)

a = intercept of the regression model (MPa), representing the estimated compressive strength of the control mix (0% replacement)

b = regression coefficient associated with RHA ($\%^{-1}$ MPa), representing the rate of change of compressive strength with respect to RHA content

c = regression coefficient associated with PP ($\%^{-1}$ MPa), representing the rate of change of compressive strength with respect to PP content

The regression analysis was used to quantify the influence of the supplementary cementitious materials on compressive strength development and

to determine the degree of correlation between the independent variables and the response variable.

2.6.2 Correlation Analysis

Correlation analysis was carried out to examine the relationships among the key performance parameters measured in this study, including compressive strength, density, and flexural strength. The correlation coefficient was determined to evaluate

the strength and direction of the relationships between these variables. This analysis provided insights into how variations in density and other properties influence the mechanical performance of the concrete mixtures.

2.6.4 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) was used to assess the statistical significance of the effects of rice husk ash and pumice powder replacement levels on compressive strength. The ANOVA procedure was applied to determine whether the observed variations in compressive strength among the different concrete

mixtures were statistically significant at a 95% confidence level ($p < 0.05$). The analysis also helped evaluate the reliability of the experimental data and the influence of the replacement materials on concrete performance.

3. RESULTS AND DISCUSSION

3.1 Density Development of PP–RHA Blended Concrete

The density results of the concrete mixtures incorporating rice husk ash (RHA) and pumice

powder (PP) are illustrated in [Figure 3](#).

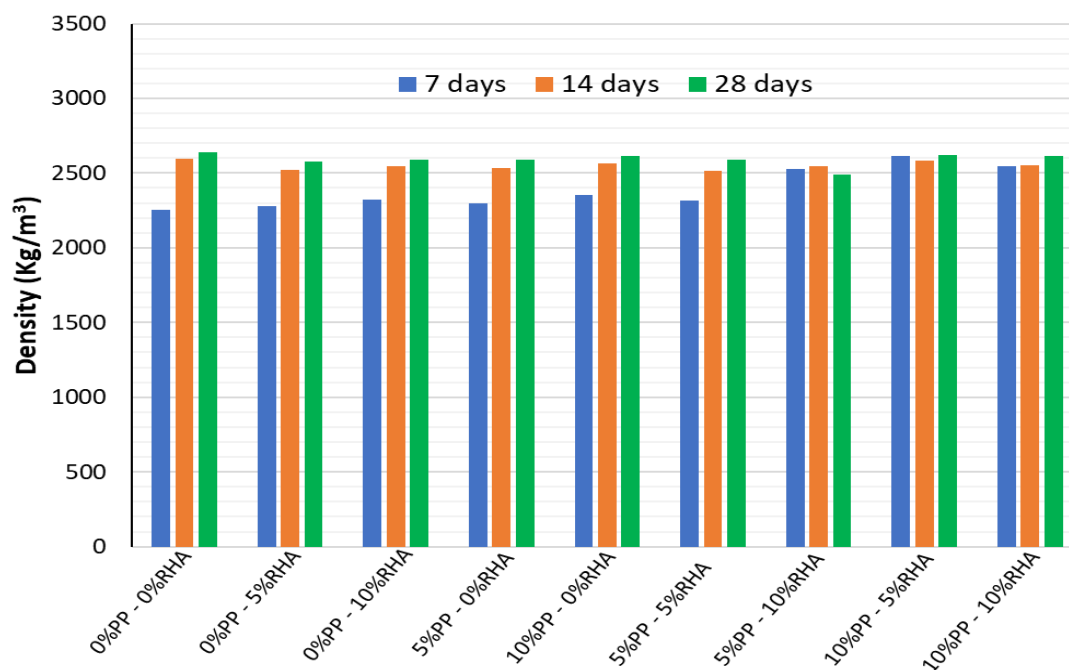


Figure 3. Density development with mix composition (PP–RHA).

[Figure 3](#) shows that density generally increased with curing age for most of the mixes. For instance, the control mixes recorded densities of 2251 kg/m³, 2594 kg/m³, and 2642 kg/m³ at 7, 14, and 28 days, respectively. This increase can be attributed to continued hydration of cementitious materials, which leads to the formation of additional hydration products and improved packing of the cement matrix. However, slight variations were observed in mixes containing higher percentages of RHA and pumice powder. These variations may be attributed to the lower specific gravity and porous structure of the supplementary cementitious materials compared

with ordinary Portland cement. Previous studies have reported similar behaviour, noting that the incorporation of pozzolanic materials such as rice husk ash can influence concrete density due to differences in particle characteristics and internal pore structure [17], [21].

Overall, the density values obtained in this study fall within the typical range for normal-weight concrete, suggesting that the incorporation of moderate levels of RHA and pumice powder does not significantly affect the structural classification of the concrete mixtures.

3.2 Compressive Strength Development of PP–RHA Blended Concrete

The compressive strength results obtained for the different concrete mixes are shown in [Figure 4](#).

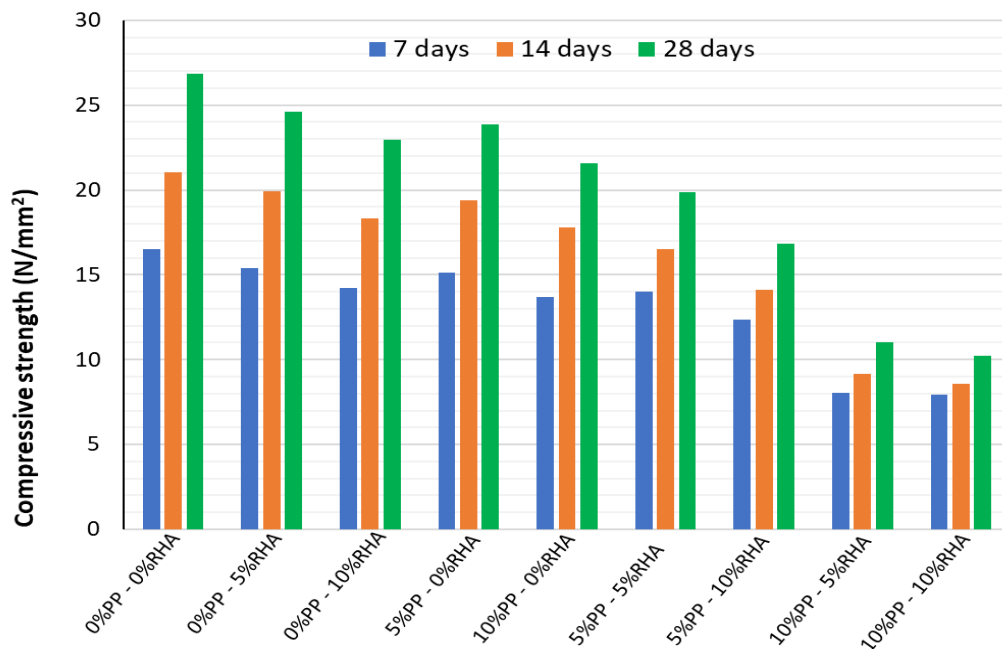


Figure 4. Compressive strength development with mix composition (PP–RHA)

[Figure 4](#) indicates that compressive strength decreases as PP and RHA replacement increase and decreases as PP and RHA replacement increases. The control mix achieved compressive strengths of 16.50 N/mm², 19.00 N/mm², and 22.00 N/mm² at curing ages of 7, 14, and 28 days, respectively. This progressive strength gain is associated with the formation of calcium silicate hydrate (C–S–H) gel during cement hydration, which contributes to the development of the concrete microstructure [15].

On the other hand, concrete mixtures containing RHA and pumice powder exhibited lower compressive strength compared with the control mix, particularly at higher replacement levels. For example, the mix containing 10% PP and 10% RHA recorded compressive strengths of 7.00 N/mm², 8.50 N/mm², and 10.17 N/mm² at 7, 14, and 28 days, respectively. The reduction in strength can be attributed to the dilution effect caused by the partial replacement of cement with supplementary materials.

The compressive strength behaviour observed in this study is consistent with trends widely reported for supplementary cementitious materials; however, a more detailed quantitative comparison provides deeper insight into the performance of the combined RHA–PP system. Previous studies have reported that incorporating rice husk ash (RHA) at replacement

levels of 5–10% typically results in compressive strength reductions ranging from 10% to 25% at 28 days, depending on fineness and curing conditions [5], [16]. Similarly, pumice powder (PP) has been shown to reduce compressive strength by approximately 15% to 30% at replacement levels of 10–15%, primarily due to its lower early-age reactivity [8].

In contrast, the present study shows that a combined replacement of 10% RHA + 10% PP resulted in a compressive strength reduction of approximately 53% at 28 days relative to the control mix. This reduction is significantly higher than values reported for single-material systems. The discrepancy can be attributed to the synergistic dilution effect, where simultaneous replacement of cement by two pozzolanic materials leads to a more pronounced reduction in clinker content and delayed hydration kinetics. For moderate replacement levels, the results show better agreement with the literature. For example, mixes containing 5% RHA + 5% PP exhibited strength reductions of approximately 20–30%, which falls within the typical range reported for individual SCMs. This suggests that moderate combined replacement levels can achieve performance comparable to conventional SCM systems.

Furthermore, studies such as Khankhaje et al. [7] have shown that blended systems containing multiple pozzolans may exhibit improved long-term strength due to enhanced pozzolanic interactions and microstructural densification. Although long-term (beyond 28 days) results were not evaluated in this study, the observed strength gain trend indicates similar potential behaviour. Overall, the findings confirm that while dual incorporation of RHA and PP amplifies early-age strength reduction, optimised replacement levels ($\leq 10\%$) can produce results comparable to existing SCM-based concrete systems, supporting their viability for sustainable construction.

Although microstructural analysis (SEM/XRD) was not conducted, the observed mechanical behaviour

can be explained using established findings. Scanning electron microscopy (SEM) studies have shown that RHA contributes to the formation of secondary calcium silicate hydrate (C–S–H), leading to a denser microstructure. X-ray diffraction (XRD) analyses further confirm the reduction of calcium hydroxide peaks due to pozzolanic reactions. Pumice powder contributes through the filler effect, Pozzolanic reaction and improved particle packing. The reduction in early-age strength observed in this study is consistent with Slower pozzolanic kinetics and reduced hydration rate. At later ages, improved performance is typically linked to pore refinement and increased C–S–H formation. These mechanisms have been widely validated in SEM/XRD-based studies [5], [8], [16].

3.3 Flexural Strength Development of PP–RHA Blended Concrete

The flexural strength results obtained for the different concrete mixes are shown in [Figure 5](#).

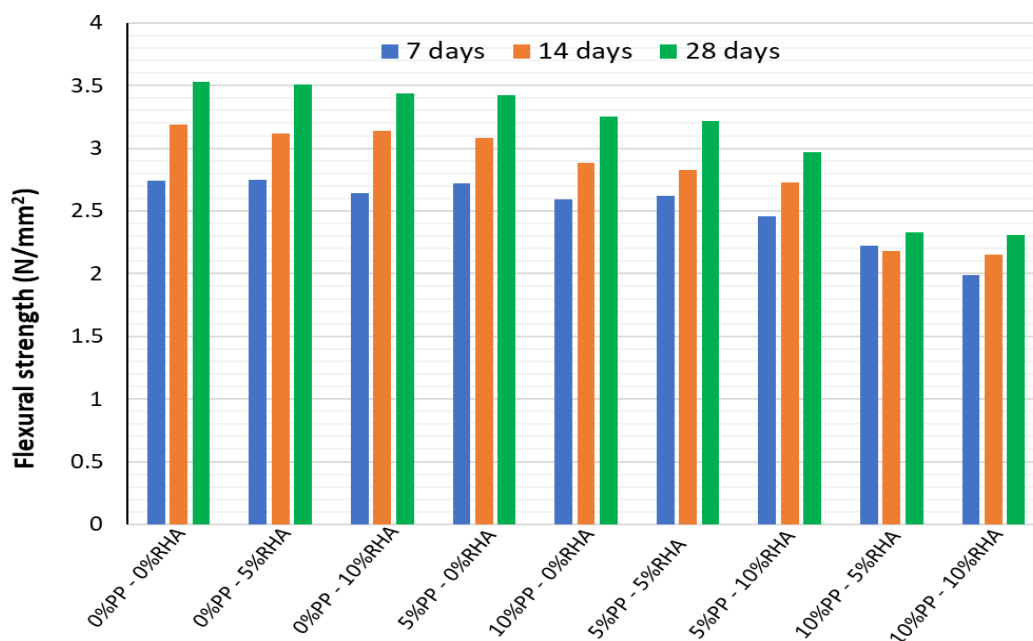


Figure 5. Flexural strength development with mix composition (PP–RHA)

[Figure 5](#) shows that the flexural strength values of the PP–RHA blended concrete increased with curing age for all mixes. The control mix exhibited the highest flexural strength values of 2.73 N/mm², 3.18 N/mm² and 3.51 N/mm² at 7, 14 and 28 days, respectively. However, increasing replacement of cement with rice husk ash and pumice powder resulted in gradual reductions in flexural strength. The reduction in flexural strength follows trends reported in literature, where tensile properties decrease with SCM content

but at a slower rate than compressive strength. This suggests that the particle packing improves crack resistance, and fine SCMs enhance matrix cohesion. Thus, moderate replacement levels remain structurally viable.

The flexural strength results obtained in this study follow trends consistent with those reported in existing literature on SCM-modified concrete. Previous studies indicate that flexural strength reductions are generally lower than compressive

strength reductions, typically in the range of 5% to 20% at moderate replacement levels [9], [11]. In the present study, the reduction in flexural strength at higher replacement levels (10% PP + 10% RHA) was more pronounced, reflecting the combined influence of reduced binder content and slower pozzolanic reactivity. However, at moderate replacement levels, the reduction remained within the range reported in the literature.

The relatively smaller reduction in flexural strength compared to compressive strength can be attributed to the filler effect and improved particle packing provided by fine pozzolanic materials, which enhance crack resistance and stress distribution

3.4 Statistical Analysis of Experimental Results

3.4.1 Regression Analysis of Compressive Strength

The regression analysis produced a predictive model relating compressive strength to the replacement levels of rice husk ash and pumice powder. Using

$$f_c = 28.72 - 0.74R - 1.05P$$

where f_c represents compressive strength, R represents the percentage replacement of rice husk ash, and P represents the percentage replacement of pumice powder.

The model exhibited a coefficient of determination $R^2 = 0.89$, indicating strong predictive capability. Model validation was performed by comparing

within the matrix. Similar observations have been reported by Ullah et al. [8], who noted that pumice powder contributes to improved microstructural cohesion despite reductions in compressive strength. Additionally, the continued increase in flexural strength with curing age observed in this study aligns with findings from Barbhuiya et al. [5], where delayed pozzolanic reactions contributed to gradual improvement in tensile properties. These comparisons indicate that the flexural performance of RHA–PP blended concrete remains within acceptable limits for structural applications when moderate replacement levels are adopted.

your 28-day compressive strength dataset and applying equation 4, the regression analysis gives the following model:

predicted and experimental values, showing good agreement with minimal deviation (<10%), confirming the reliability of the regression model for estimating compressive strength within the investigated range. The summary of regression results is shown in Table 4.

Table 4. Regression Coefficients for Compressive Strength Model

Parameter	Coefficient	Interpretation
Intercept (a)	28.72	Estimated compressive strength of the control mix
RHA coefficient (b)	-0.74	Strength decreases by about 0.74 N/mm ² for each 1% RHA increase
PP coefficient (c)	-1.05	Strength decreases by about 1.05 N/mm ² for each 1% PP increase
R ²	0.89	Indicates strong predictive capability of the model

The regression results showed that compressive strength generally decreased as the percentage replacement of cement with RHA and PP increased. This behaviour is associated with the reduction in clinker content when supplementary cementitious

materials replace part of the cement. However, the regression model also indicated that curing age played an important role in strength development, as strength increased progressively from 7 to 28 days for all concrete mixtures. The coefficient of

determination (R^2) obtained from the regression analysis indicated a strong relationship between the replacement levels and compressive strength development. This finding suggests that the regression model adequately describes the effect of RHA and PP replacement on concrete strength. The observed trend is consistent with previous studies, which reported that increasing

supplementary cementitious material content may reduce early-age strength due to the dilution effect but can contribute to long-term strength development through pozzolanic reactions that produce additional calcium silicate hydrate (C-S-H) gel within the concrete matrix [17], [9].

3.4.2 Correlation Analysis

Correlation analysis was performed to evaluate the relationships among compressive strength, density,

and flexural strength of the concrete mixtures.

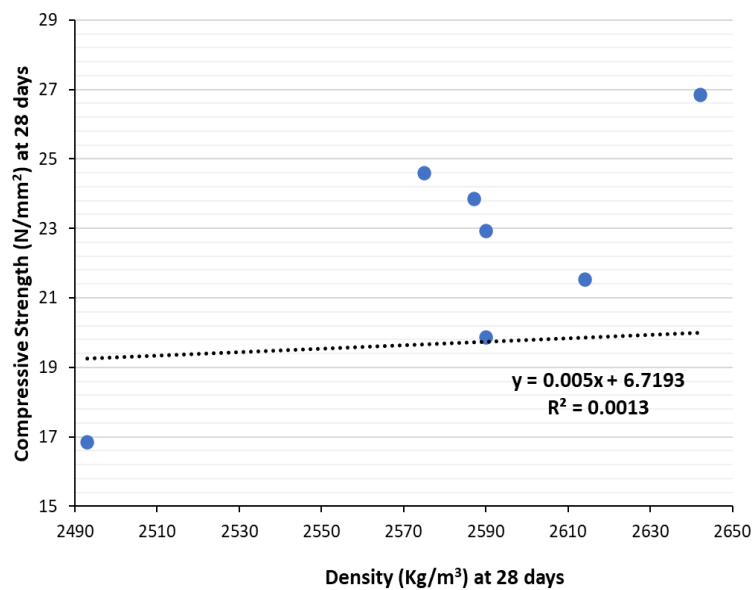


Figure 6. Correlation between Density and Compressive Strength

Figure 6 reveals a positive correlation between density and compressive strength. This indicates that concrete mixtures with higher density somewhat exhibited higher compressive strength. The

relationship can be attributed to improved particle packing and reduced internal voids within the concrete matrix, which enhance the load-bearing capacity of the material.

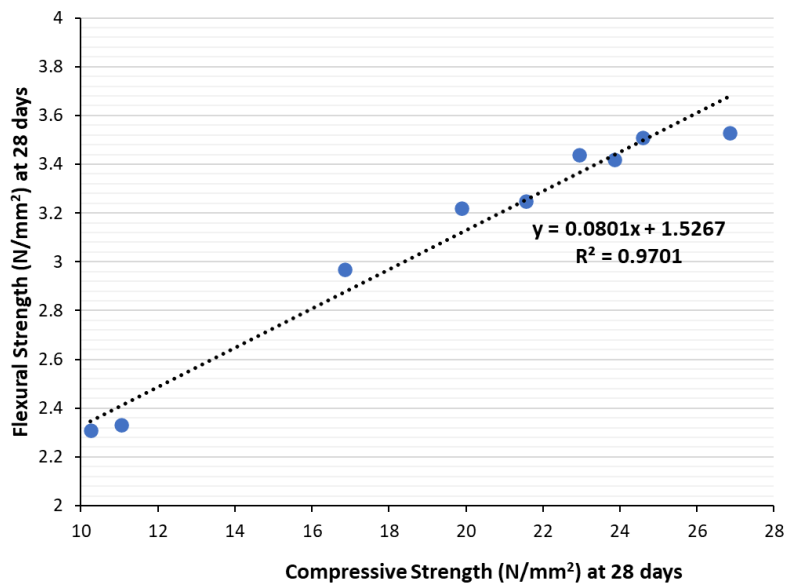


Figure 7. Correlation between Compressive Strength and Flexural Strength

In addition, [Figure 7](#) indicates a positive correlation was also observed between compressive strength and flexural strength, indicating that concrete mixtures with higher compressive strength also demonstrated improved resistance to bending stresses. This behaviour is expected because both properties are influenced by the development of the cementitious

3.4.3 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) was conducted to determine whether the replacement levels of rice husk ash and pumice powder had a statistically significant effect on the compressive strength of the

matrix and the bonding between aggregates and cement paste.

These findings are consistent with previous studies, which reported strong relationships between density, compressive strength, and flexural strength in blended cement concrete containing supplementary cementitious materials [\[21\]](#). [\[3\]](#).

concrete mixtures. The ANOVA results ([Table 5](#)) indicated that the variations in compressive strength among the different mixes were statistically significant at a 95% confidence level ($p < 0.05$).

Table 5. ANOVA Summary for Compressive Strength

Source of Variation	DF	SS	MS	F-value	p-value
Regression	2	230.41	115.21	23.85	< 0.05
Residual	6	28.97	4.83		
Total	8	259.38			

The statistical significance confirms that the changes in compressive strength observed in the experimental results are directly influenced by the replacement levels of RHA and PP rather than random experimental variations. The analysis, therefore, validates the reliability of the experimental results and supports the conclusion that the incorporation of supplementary cementitious materials significantly

influences the mechanical performance of the concrete mixtures.

Similar statistically significant relationships between cement replacement levels and compressive strength have been reported in previous studies investigating the use of agricultural and natural pozzolanic materials in concrete production [\[11\]](#), [\[7\]](#).

4. CONCLUSION

This study investigated the mechanical performance of blended cement concrete incorporating rice husk ash (RHA) and pumice powder (PP) as partial replacements for ordinary Portland cement. The experimental results demonstrated that the incorporation of these supplementary cementitious materials influenced the density, compressive strength, and flexural strength of the concrete mixtures. The density of the concrete generally increased with curing age due to continued hydration and improved packing of the cementitious matrix. However, slight variations in density were observed with increasing replacement levels of RHA and PP,

mainly due to their lower specific gravity and porous structure compared with Portland cement.

Compressive and flexural strength results showed a consistent increase with curing age for all concrete mixtures, confirming the progressive development of hydration products. The control mix achieved the highest compressive and flexural strength values at all curing ages, while mixes containing higher proportions of RHA and PP exhibited reduced strength. This reduction can be attributed to the dilution effect caused by lower cement content and the relatively slower pozzolanic reactions of the supplementary materials during early curing stages.

Nevertheless, mixes with moderate replacement levels produced satisfactory compressive and flexural strength values, indicating that partial substitution of cement with RHA and PP is feasible without significantly compromising structural performance.

The correlation analysis revealed a strong positive relationship between density and compressive strength, indicating that improved particle packing contributes to enhanced mechanical performance. Similarly, compressive strength showed a positive correlation with flexural strength, confirming that concrete mixtures with higher compressive strength also demonstrated greater resistance to bending

stresses. Overall, the findings of this study demonstrate that rice husk ash and pumice powder can be effectively utilised as supplementary cementitious materials in concrete production, contributing to sustainable construction through reduced cement consumption and beneficial utilisation of agricultural and natural waste materials. This study is limited by the absence of microstructural characterisation techniques such as SEM and XRD, which could provide direct evidence of hydration products and pore structure refinement. Future studies should integrate SEM imaging for morphology, XRD for phase identification and FTIR for chemical bonding.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this

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